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# Fundamental and Harmonic Emission in Interplanetary Type II Radio Bursts

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# FUNDAMENTAL AND HARMONIC EMISSION IN INTERPLANETARY TYPE II

## RADIO BURSTS

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## ABSTRACT

Three interplanetary type II radio bursts which show two prominent and long duration bands in their dynamic spectra are analyzed in detail and are compared to similar bands in meter wavelength type II events. These bands, which differ by a factor of about 2 in frequency, are interpreted in terms of fundamental and harmonic emission. The fundamental component has a greater average intensity than the harmonic, due largely to short intense brightenings. The fundamental spectral profile is more narrow than that of the harmonic, with harmonic band typically exhibiting a larger bandwidth to frequency ratio than the fundamental by a factor of 2. The fundamental has a larger source size than the harmonic, 160 degrees versus 110 degrees, on average, as viewed from the sun. Two of the events have source positions which correlate well with the associated flare positions.

## I. INTRODUCTION

The type II solar radio burst results from the excitation of the coronal plasma by a shock wave propagating outward from the sun. Although type II bursts have been extensively studied in ground-based observations at meter wavelengths, corresponding to heights of about 1 - 5 solar radii ( $R_0$ ) above

the solar surface, relatively few studies of the interplanetary (IP) type II events, which are seen at kilometer wavelengths, have been reported (for reviews see Kundu, 1965; Kruger, 1979). Earlier papers by Cane et. al. (1982) and Cane and Stone (1984) have discussed general features of interplanetary type II events, as observed by the ISEE-3 spacecraft. These papers focussed on identifying IP type II events and studying correlations with flare related phenomena.

This paper is a study of three unusual interplanetary type II events which show two prominent bands in their dynamic spectra. The bands are separated by a factor of about 2 in frequency, and the peak intensities of the bands are at least 50 percent greater than the intensity of the underlying emission. Moreover, the bands have a long duration, on the order of  $3/4$  of a day, which represents a large fraction of the total event duration (typically about 2 days). Interplanetary type II events with such characteristics are rare in our data; only 3 out of about 40 identified type IIs observed by ISEE-3 (Cane and Stone, 1984) show such clearly defined bands. However, many of the remaining events do show evidence of two components at times, but these components tend to be weak or not clearly distinguishable.

The three events studied in this paper began on November 22, 1980, September 4, 1982, and February 3, 1983, and are designated as 801122, 820904, and 830203, respectively. Table 1 shows the flare associations and meter wavelength activity for each event. The three events have reasonable associations with flares, sudden commencements at earth, and meter wavelength activity. The velocities shown in the table are derived from the time between the flare at the Sun and sudden commencement at 1 AU. These velocities are similar to those found by Cane and Stone (1984) for more than 30 type II events. The transit velocities for the three events range from 640 to 1200 km/sec, which is typical of the velocity range of all the identified IP type II events; this would imply that the existence of a double-banded structure in IP type II events is not a function of shock velocity alone.

Ground-based studies by Roberts (1959) of 65 meter wavelength type II events, and by Maxwell and Thompson (1962) for 138 events show that 60 to 80 percent of these events display two prominent bands in their dynamic spectra; these bands have been interpreted to be due to emission at the fundamental and second harmonic of the local plasma frequency.

In the following analysis, we will refer to the lower frequency band

TABLE 1

Flare and meter wavelength activity for the IP type II events.

<u>EVENT</u>	<u>FLARE MAX (UT)</u>	<u>FLARE COORD</u>	<u>TRANSIT VEL (KM/SEC)</u>	<u>METER WAVE ACTIVITY</u>
801122	0554	S17E40	640	II (?)
820904	0200 <sup>+</sup>	N11E30 <sup>++</sup>	900	
830203	0619	S19W08	1200	II/IV

+ Probable start of associated SA event.

++ From Harvey and Recely, 1984.

in our data as the F component, and to the higher frequency band as the H component.

## II. OBSERVATIONS

The ISEE-3 radio experiment has been discussed by Knoll et al. (1978), and techniques for extracting source direction and angular size have been discussed by Fainberg (1979). The experiment consists of 2 dipoles, one spinning in the ecliptic plane and the other oriented along the spin axis. The data provided by the instrument are antenna temperature, modulation index and source azimuth. The modulation index provides a measure of source size, and the azimuth is the centroid of positions of all sources in the field of view.

The experiment records the data in 23 separate frequencies ranging from 2 MHz to 30 KHz; plasma frequencies in this range correspond to heights of approximately 10  $R_0$  to 1 AU above the sun. The separation of the frequency channels of the receiver increases toward higher frequency, ranging from about 10 to 100 KHz over most of the frequency range, resulting in a less complete frequency sampling at high frequency.

### A. Dynamic Spectra

Dynamic spectra are produced for the data, an example of which is shown in Figure 1 for event 820904. General characteristics of our dynamic spectra have been discussed by Cane et al. (1982). Briefly, the spectra show frequency decreasing along the vertical axis from 2 MHz to 30 KHz, and time increasing along the horizontal axis. The degree of darkness at each point is proportional to the intensity of emission. The event is visible on the spectra from about 0800 UT on September 4 to about 2200 on September 5, when a sharp increase in the emission intensity at all frequencies signals the passage of the shock at the spacecraft (Hoang et al., 1980).

Two bands of emission which slowly drift toward lower frequency on the dynamic spectra are evident for more than half a day. These are the F and H bands. The drift toward lower frequency corresponds to the steady increase in the heliocentric height of the type II emission as the shock moves outward from the sun. The bands are somewhat sporadic, and the F band exhibits

noticeable intensity variations. Intense brightenings may last a few hours or more. An example is at about 2200 UT on September 4 in the F band.

### B. Intensity Spectra

Spectral plots, log intensity vs log frequency, have been generated for each event. This is analogous to a vertical cut through the dynamic spectra. The spectra have been produced from half hour averages of the data, and some examples are shown in Figure 2a for 820904 and in 2b for 801122. The frequency scale ranges from 500 KHz on the right to 30 KHz on the left. The data on these plots have been corrected by subtracting the galactic background at the highest frequencies, and an average low frequency (LF) thermal noise continuum at the lowest frequencies (Hoang et al., 1980).

Two prominent peaks appear in the spectra shown in Figure 2; they are separated by about a factor of 2 in frequency and correspond to the F and H bands seen in the dynamic spectra. The peaks are used to define frequencies, intensities and half power bandwidths for each band.

The spectral profile shapes are quite varied and typically asymmetric. Typical profiles, as shown in Figure 2, are characterized by a narrow, often intense F peak, with the broader H component at roughly twice the frequency of the F component. The low frequency side of the profile is normally steeper than the high frequency side. Emission often occurs over a large fraction of the observed frequency range at any one time. In Figure 2a, emission is evident from at least 500 KHz down to about 50 KHz. Profiles in both Figures 2a and b are clearly asymmetric, and large variations are seen in the F component.

Some ground-based observations of meter wavelength type II's have shown similar characteristics. Published spectral profiles of metric type II bursts (Wild et al., 1954) showed that for two events the H band was broader and more symmetrical than F, which seemed to show a steep low frequency side. Roberts (1959), however, found that profiles of F and H bands of five events were similar in shape.

## III. RESULTS

### A. Frequency

Frequencies at the peaks of F and H spectral features have been measured. The peak frequencies show a drift with time toward lower frequency or greater height, with typical drift rates of from about 1000 KHz/hr at 1 MHz down to a few KHz/hr at 60 KHz.

The average H/F frequency ratios measured are slightly less than 2, but during an event these ratios may range from about 1.7 to 2.4. Figure 3b shows H/F ratios for event 830203. In this case the H/F frequency ratio is greater than 2 for many hours early in the event, and less than 2 later on.

The meter wavelength type II events studied by Roberts (1959) have shown a mean ratio of about 1.95 for all events, with a range of 1.85 to 2.05 for individual events. For the FH events studied by Maxwell and Thompson (1962) the mean ratio was about 1.90.

## B. Intensity

From the peaks of the F and H features intensities have been measured in units of  $\text{watts/m}^2/\text{Hz}$ . Figure 4 shows a plot of log intensity vs time for 820904. For much of the event F and H components have similar intensities, but during some intervals the F band shows a large increase in strength of up to 20 dB lasting for many hours. For the other 2 events studied, F is typically more intense than H throughout the event and intense brightenings are common, sometimes lasting hours. The H component tends to be more uniform in intensity, with variations of the order of a factor of 2. The F component is much more variable in general with typical enhancements of a factor of 10 to 1000. The average values of F and H intensities are shown in Table 2. For the three events, the F component averages about  $4 \times 10^{-19} \text{ watt/m}^2/\text{Hz}$ , while the H component is about a factor of 10 weaker.

In ground-based studies a wide range of intensity ratios has been found. In their study Maxwell and Thompson (1962) found F and H intensities to be similar to each other, usually greater than  $10^{-19} \text{ watt/m}^2/\text{Hz}$ . Roberts (1959) found similar results, with some events showing stronger F and others stronger H bands. Weiss (1963) reported that for bursts associated with flares near the limb, H was much more intense than F, which appeared more patchy and less well defined. Wild et al. (1954) found F more variable in intensity than H in two events. The F emission seemed to occur in short duration bursts.



TABLE 2

Average values of F and H component parameters for each event.

<u>EVENT</u>	<u>BANDWIDTH/FREQ RATIO</u>		<u>INTENSITY (SFU)</u>		<u>ANGULAR SIZE (DEG LONGITUDE)</u>	
	F	H	F	H	F	H
801122	0.15	0.35	600	80	160	130
820904	0.16	0.38	7000	500	150	100
830203	0.19	0.47	4000	1000	150	90

Intensities in solar flux units ( $\text{watts/m}^2/\text{Hz}$ ).

### C. Bandwidth

Bandwidths have been measured from the F and H features on frequency spectra, as discussed above. Figure 5a is a plot of the half-power bandwidth vs time for the two bands of event 820904. The other 2 events show bandwidth plots similar to Fig. 5a. There is an overall decrease in bandwidth with time for both bands. The H band has a larger bandwidth than F, for all the events, usually by a factor of 4 or so. We might have expected the bandwidth of H to be about twice that of F if the H profile were created by duplicating each point in the F profile at twice the frequency of the point.

In Figure 5b each point represents bandwidth divided by the peak frequency ( $bw/f$ ) of the spectral profiles in event 820904. For the reason mentioned above, the  $bw/f$  ratio of F might be expected to be about the same as for H. Figure 5b shows that the bandwidth to frequency ratio is greater for the H component than for the F in general. Usually the  $bw/f$  ratio stays relatively constant with time for the three events.

Table 2 shows the average  $bw/f$  ratios for each band of the 3 events. In general, the H component has a larger  $bw/f$  ratio than the F band, with H about twice as large as F for an event. The average  $bw/f$  for F is 0.17 and about 0.4 for H.

From ground-based observations  $bw/f$  ratios of 0.3 (Maxwell and Thompson, 1962) and 0.03 (Wild et.al., 1954) have been reported. Roberts (1959) reported very narrow bandwidths. Boischot et.al. (1980) found a value of 0.1 for interplanetary type II events seen by the Voyager spacecraft. These studies do not indicate that any differences between F and H  $bw/f$  ratios were found.

### D. Source Position

Positions observed by ISEE correspond to the centroid of all sources in the field of view at any time. The positions are measured as longitude of the source centroid east or west of the central meridian. We have used the observed source positions to calculate positions as viewed from the sun, assuming a density scale found to be reasonable for our observed type II events. A plot of this is shown in Figure 6 for 830203. The flare associated with this event is at W 08 longitude on the sun, and this position is

indicated on the figure. The F positions generally cluster near the flare longitude to within about 20 degrees, while the H sources lie a bit farther to the east of the flare. Both bands show occasional abrupt changes in source position, by ten's of degrees in some cases.

For 801122 also, positions for both F and H sources have been found to lie within about 20 degrees of the flare longitude, on average. Abrupt changes in position are evident at times in both components, but the overall trend is toward a reasonable association of flare and type II longitudes. For 820904, however, there is not a good correlation between source and flare longitudes. Indeed, for this event the F and H centroids tend to lie on opposite sides of central meridian.

It is interesting that the measured positions are reasonably consistent for each band, at least out to 100  $R_0$  or so. If local random brightenings along the shock front dominated the emission, one might expect a more random behavior of source position to be observed. We see no evidence that the F and H positions have been shifted in any systematic way relative to the flare position, or to each other. For all 3 events the F positions show a larger scatter than the H positions, especially later in the events.

Studies of meter wavelength events have shown a tendency for the H component to lie inside (toward central meridian) the F position, for simultaneously measured F and H components (Weiss, 1963). F and H sources measured at the same frequency (different times) tend to coincide. Many events have shown abrupt changes in source position, attributed by Weiss (1963) to multiple regions along the shock randomly brightening due to changing physical conditions. However, there seems to be less of a variation in the H source position than in the F position. There do not seem to be systematic differences in F and H positions relative to the flare, but in almost all cases both F and H lie on the same side of central meridian as the flare.

#### E. Source Size

The modulation index measured by ISEE can be used to calculate the size of sources, based on assumptions about the intensity distribution and source shape. The source is assumed to be in the ecliptic plane. If the source lies out of the ecliptic it will have a smaller size than calculated. The

dependence of source angular size, as viewed from ISEE, on modulation index is calculated using formulae given by Fainberg (1979). The dipole antenna has poor spatial resolution; therefore, the modulation of a finite source due to the spin of the antenna is used to determine source size. Since we cannot determine source structure, our derived angular sizes indicate the approximate angular extent of the overall emission.

Using an appropriate electron density scale and simple model of source shape, we can compute the source size as viewed from the sun. Table 2 summarizes the average angular size subtended at the sun for each event for F and H components separately. There is an obvious difference between F and H sizes for each event, with F larger than H by more than 30 degrees. A plot of angular source size for 820904 is shown in Figure 7 from about 25  $R_{\odot}$  to 150  $R_{\odot}$ . For this event the size of the F component remains fairly constant, implying the F component undergoes roughly spherical expansion. The H band shows an initial decrease in angular size, but thereafter is fairly constant. For other events source size may increase or decrease as the shock moves outward, implying greater than or less than spherical expansion. The calculated angular size during an event may change by up to 20 degrees in either band.

In ground-based studies large source sizes are also found. Kai and McLean (1968) reported type II emission from an area the size of the solar disk using Culgoora radioheliograph observations at 80 MHz. Dulk and Smerd (1971) used the same instrument and observed type II emission over an 80 degree arc around the disk. In a study of 3 type II bursts with F and H bands, Nelson and Sheridan (1974) found that in all cases the F sources were much larger than the corresponding H sources, with differences larger than those calculated from scattering models.

#### IV. DISCUSSION

##### A. Summary of Kilometric F and H Observations

Table 3 lists the H/F ratios for the parameters discussed above for the 3 events studied. The main observational results of this study may be summarized as follows:

TABLE 3

H/F ratios for measured parameters of each event.

<u>EVENT</u>	<u>FREQUENCY RATIO</u>	<u>BAND/FREQ RATIO</u>	<u>INTENSITY RATIO</u>
801122	1.97	2.3	0.14
820904	1.85	2.4	0.05
830203	1.99	2.5	0.17

1. The F and H source positions for 2 of the 3 events appear to correlate well (usually to within 20 degrees) with the longitude of the flare associated with the event.
2. The simultaneous F and H position centroids differ, sometimes by ten's of degrees and show no systematic displacement from each other or from the flare. The F component shows a larger scatter in position than the H component.
3. The H/F frequency ratios are typically less than 2, on average, with a range of between 1.7 and 2.4.
4. The half-power bandwidth to frequency ratio for H is generally greater than for F by a factor of about 2.
5. Spectral profile shapes are quite varied, the low frequency side typically steeper than the high frequency side. The H component usually is more rounded and the F feature is more sharply peaked.
6. Angular source sizes of F components tend to be about 30 degrees or more larger than corresponding H sources, as viewed from the sun.
7. The occurrence of a two-banded structure in IP type II events does not seem to depend on shock velocity.

We have looked for correlations among the various observed parameters which might improve our understanding of these phenomena. For instance, if intense brightenings, as seen often in the F band, are due to the excitation of a localized region of the shock front, we might expect to measure for these brightenings source sizes and bandwidths noticeably smaller than average for the event. We do see decreases of about 10 degrees in size for some intervals during intensity enhancements, but there are many other intervals where no changes occur. Investigation shows that source sizes, bandwidths, and positions show no clear correlation with intensity fluctuations. We have also not seen obvious correlations among sizes, bandwidths, positions, or other measurements.

#### B. Comparisons of Kilometric and Metric Observations

It is difficult to draw general conclusions from comparisons between

metric and kilometric type II events due to the small number of events in both categories for which the same properties have been accurately measured. Two characteristics which clearly differ between metric and IP events are that most metric events show two obvious bands in their dynamic spectra while few IP events do, and that many metric bursts (about 20 percent) show some evidence of herringbone structure, fast drift features emanating from the type II bands (Roberts, 1959), while IP events do not.

Some metric type II's have been reported with  $bw/f$  ratios similar to our measurements (about 0.3), whereas other metric studies have found ratios a factor of 10 lower.

Our derived source sizes agree with the findings of Nelson and Sheridan (1974) which show that the F sources are significantly larger than the corresponding H sources. Type II events at both metric and kilometric wavelengths are very large, subtending angles at the sun of from 80 degrees to close to 180 degrees.

The events we have studied show an average F/H intensity ratio of about 10. This is unlike metric events, where in general the intensities of the two bands are similar, and in some events near the limb, the H band is much stronger than F. It is interesting, however, that in these limb events the F band is very sporadic and displays an erratic intensity distribution. This is similar to the behavior of the F band in our data.

Ground-based studies have shown a tendency for the H source to lie inside of F for simultaneously measured bands. We see no similar trend in our data, but our results tend to agree with Weiss (1963) that the variation in H positions seems to be less than the variation in F.

Differences between metric and kilometric type II events might be due to differences in propagation properties between the two height regimes. It is also possible that the metric and IP events are intrinsically different. For instance, it has been suggested that coronal and IP II's associated with the same flare are actually emitted by different shocks; the coronal event might be related to a blast wave and the IP event to a shock which is driven outward, at least initially (Cane, 1983). To investigate this hypothesis, it would be useful to compare intensities, bandwidths, source positions, etc., of metric and IP type II events which occur at similar times to ascertain whether these events might be physically related.

### C. Interpretations of Kilometric F and H Bands

The observations of two-band structure in interplanetary type II radio bursts are best interpreted as fundamental and harmonic emission from the interplanetary plasma. Several findings support this. Obviously the frequency ratio averaging about 2 for the two bands in all 3 events analyzed is consistent with the hypothesis of fundamental and harmonic emission. The larger size of F sources relative to H observed by ISEE also agrees with the F-H interpretation since frequencies near the plasma frequency are expected to be scattered more than higher frequency emission (Leblanc, 1973). Erratic intensity changes in F are not surprising since emission near the plasma frequency is sensitive to propagation effects, e.g. scattering and wave ducting (Bougeret and Steinberg, 1977; Duncan, 1977), and so the F emission is likely to be more variable than the H emission (Dulk and Suzuki, 1980; Steinberg et al., 1984; Dulk et al., 1984).

The smaller  $bw/f$  generally found for F is also not surprising since fundamental components in type III bursts are known to be highly directive, much more so than the harmonic (Caroubalos et al., 1974; Dulk and Suzuki, 1980). This means that the beam pattern of the fundamental is more narrow than that of the harmonic, such that the fundamental is likely to be received from a more narrow range of angles along the shock front. Therefore, even if F and H sources are generated in the same regions along the shock, H is more likely to be observable at earth from a larger number of source regions at any one time, and therefore presumably from a larger frequency range. Its instantaneous bandwidth to frequency ratio will therefore be greater.

Positions and peak frequencies will also be dependent on directivity effects, which could explain why simultaneous F and H sources have different observed position centroids and why H/F frequency ratios at times differ from 2 by up to 20 percent for the IP events. Due to these effects, F emission from some regions may not be transmitted to earth as readily as H emission from the same regions. This would tend to displace the position centroid of the observable F sources from the H centroid. This might also account for the greater scattering observed in the position centroids of the F component compared to the H. Certain frequency components of the F band might not propagate to the observer, in which case the F spectral profile would be altered such that the H/F frequency ratio could deviate from 2 at times.



Another effect which could also influence source positions, frequencies, etc., is that F and H sources might at times be emitted from separate regions along the shock. The intense brightenings seen in the F band but not simultaneously in the H component appear to be an indication of this. It is likely that these brightenings occur under conditions which favor F emission over H emission. If some F and H sources along the shock can be emitted from different regions, then the position centroid of these sources may well differ, and the frequency ratio may deviate from 2, depending on how the electron density structure changes along the shock front.

We cannot positively rule out, but find unlikely, the interpretation that the bands seen in the interplanetary type II's are due to emission occurring ahead of and behind a strong shock, where the electron density jump across the shock is a factor of 4, causing a frequency ratio of 2. This same explanation would not be applicable to the two-band meter wavelength type II's, presumably, since up to 80 percent of metric II's have 2 harmonically related bands; it seems unlikely that most metric II's are associated with strong shocks. If this idea were correct, one might expect some events associated with weaker shocks would also emit similar bands, with frequency ratios anywhere between 1 and 2. This has not been reported.

It is also unlikely that the bands we see are due to multiple shocks, which occasionally have been observed by in situ measurements (e.g. Scarf, et.al., 1972). To explain our results, one would have to postulate 2 shocks with velocity ratios of about 2 for all 3 events. We see no good evidence for the passage of a second shock at ISEE at about twice the time interval of the observed shock passage.

## V. CONCLUSIONS

We have reported quantitative measurements of interplanetary type II event characteristics, including frequencies, intensities, bandwidths, source positions and sizes for three events displaying strong bands in their dynamic spectra, and conclude that the observed bands are due to fundamental and harmonic plasma radio emission.

We find that compared to the harmonic, the fundamental component is generally more intense and variable, has a larger source size and a smaller

bandwidth to frequency ratio, and its spectral profile is more sharply peaked. Differences in properties of the fundamental and harmonic components may be due to intrinsic differences as well as to propagation effects.

We have restricted this study to those events in which we have observed a prominent double-banded structure in the dynamic spectra. This work is being expanded to encompass the remaining type II events observed by ISEE-3, and will be reported on in a future paper.

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#### FIGURE CAPTIONS

Fig. 1 Dynamic spectrum for interplanetary type II event 820904. The frequency range is 2 MHz to 30 KHz along the vertical axis. The horizontal axis is divided into hours. The type II event appears

as two bands slowly drifting toward lower frequency.

Fig. 2 a) Spectra for 820904. Two main peaks are evident below 200 KHz.

The low frequency peak, or F component, is more variable and sharply peaked than the higher frequency H component. High frequency emission with a peak above 200 KHz is often seen; the origin of this emission is unclear.

b) Spectra for event 801122. The F and H peaks are between 100 and 300 KHz.

Fig. 3 Frequency ratio of H to F components for event 830203. The ratio changes during the event, starting near 2.2 and ending at about 1.7.

Fig. 4 Peak intensity versus time for F (dots) and H (triangles) components of event 820904.

The F emission is highly variable, brightening by factors greater than 100. The H component is more constant in intensity.

Fig. 5 a) Bandwidth versus time for F (dots) and H (triangles) components of event 820904.

The H bandwidth is larger than F by about a factor of 4.

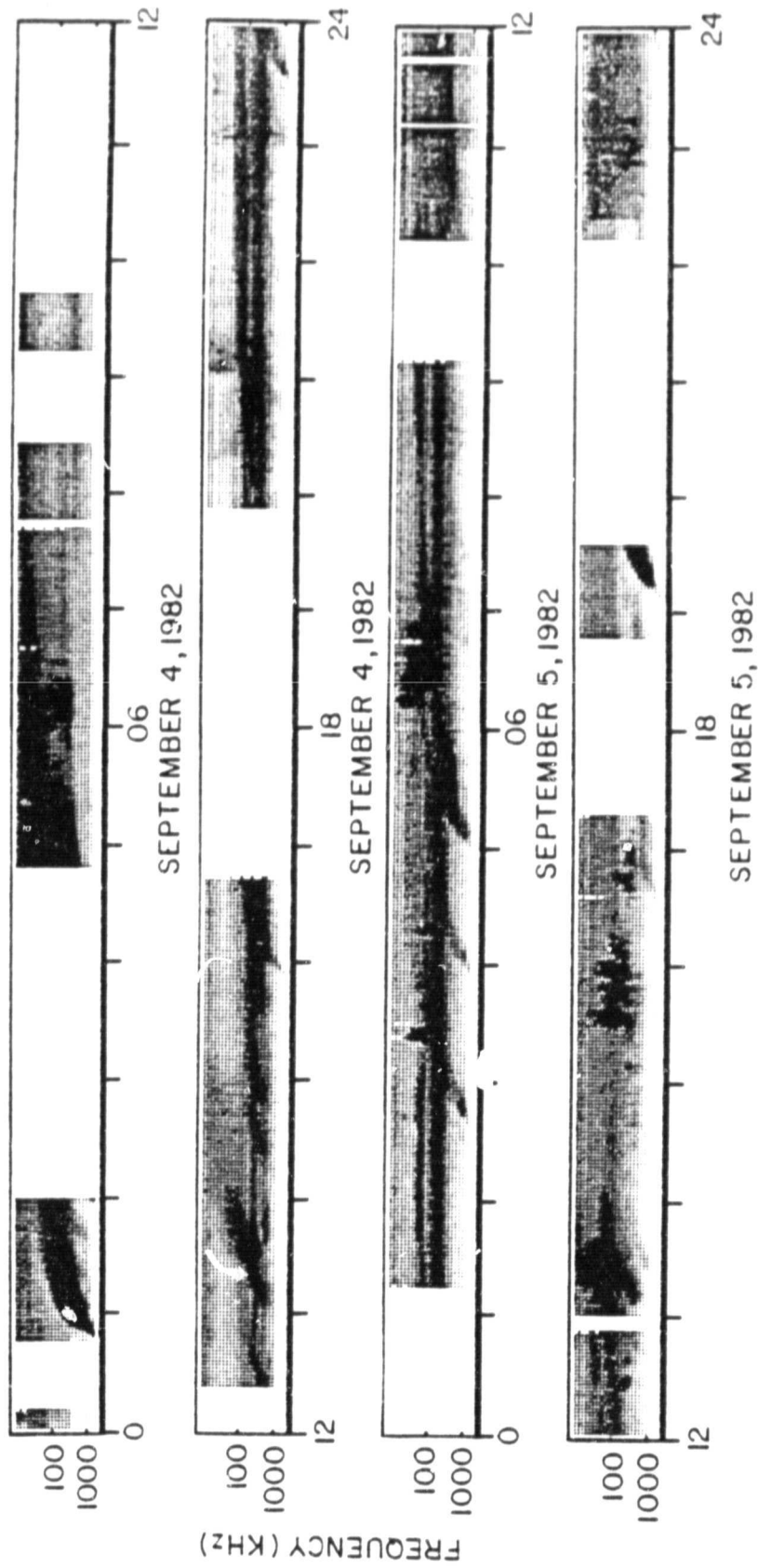
b) Bandwidth to frequency ratio for F (dots) and H (triangles). Again the H ratio is larger, by about a factor of 2.

Fig. 6 Longitude of F (dots) and H (triangles) source centroids for 830203.

The simultaneous F and H centroids are typically separated, but both are reasonably well associated with the flare position.

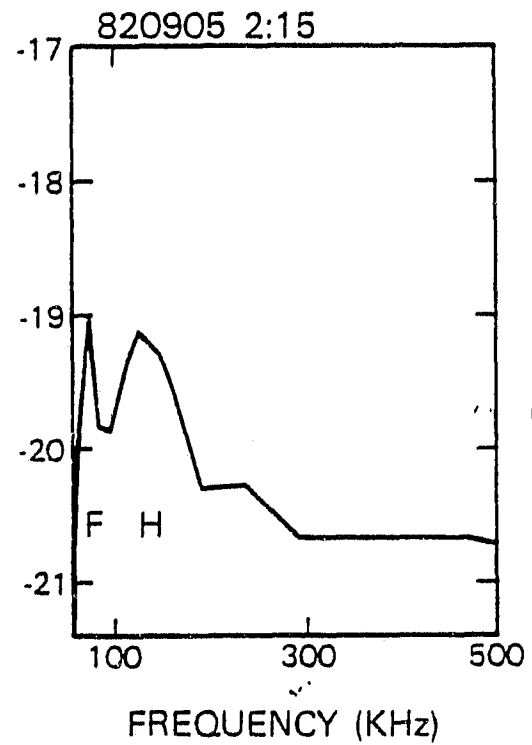
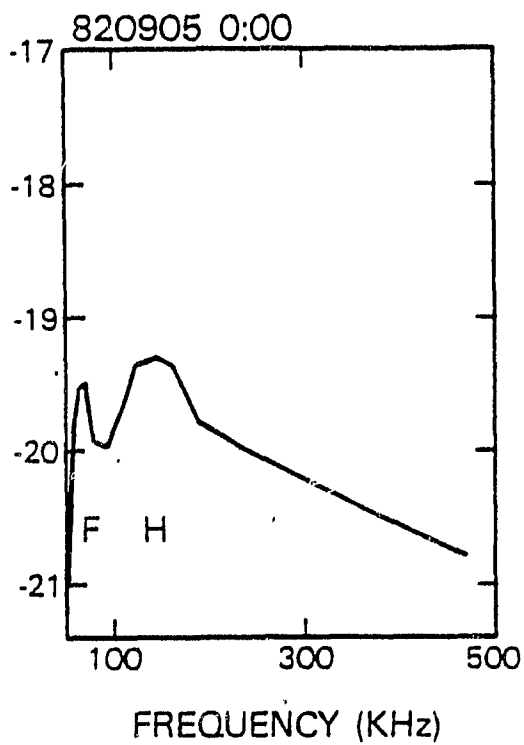
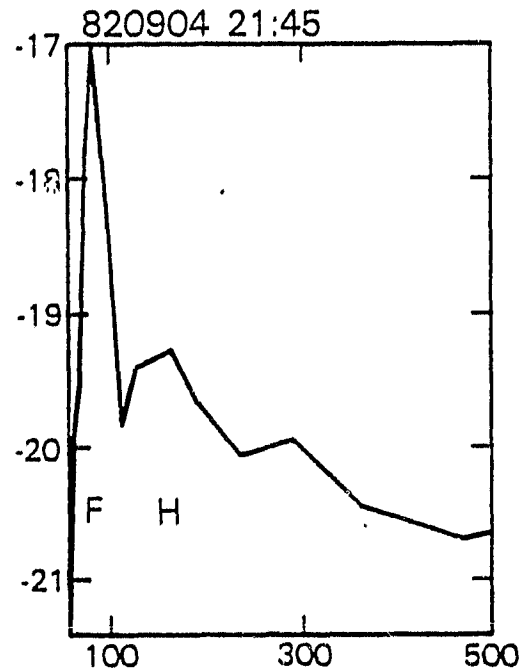
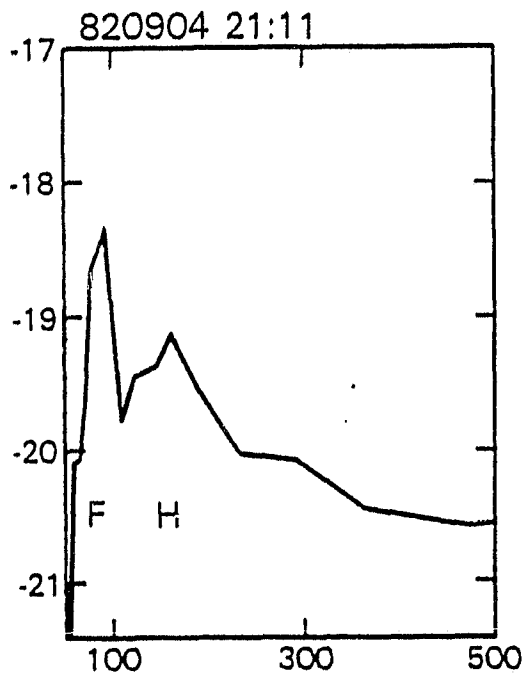
Fig. 7 Source size versus time for F (dots) and H (triangles) components of 820904. Source size is as viewed from the sun. A clear separation is apparent for F and H sizes, with F always larger by at least 30 degrees.

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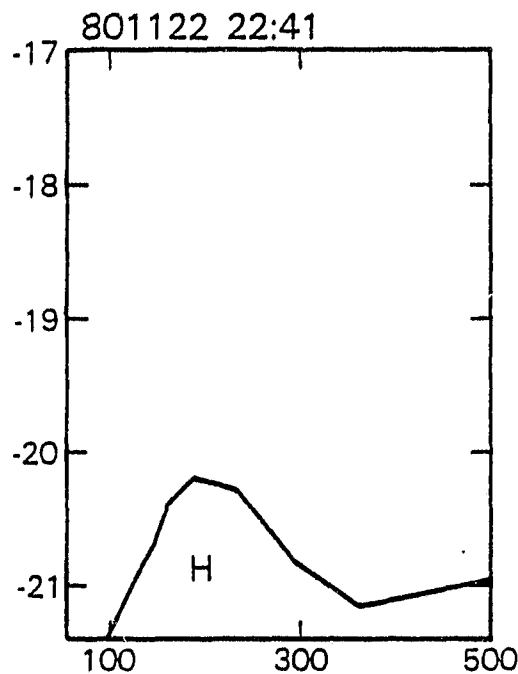
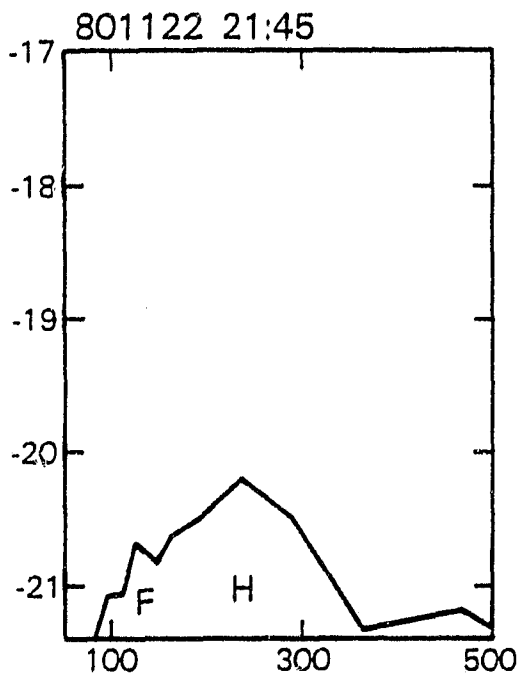
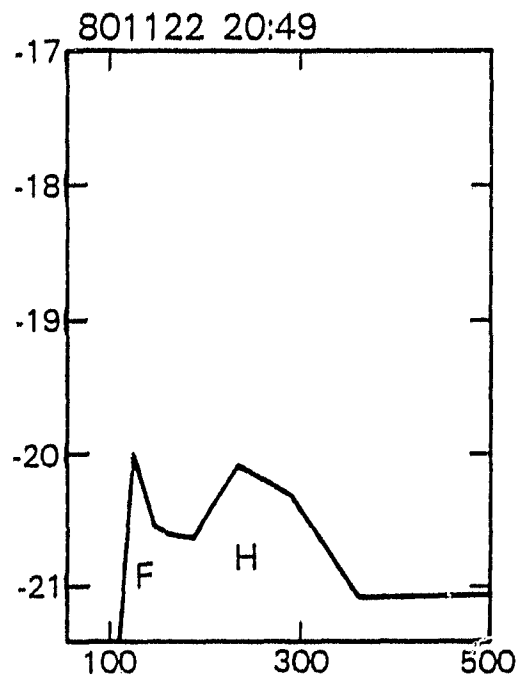
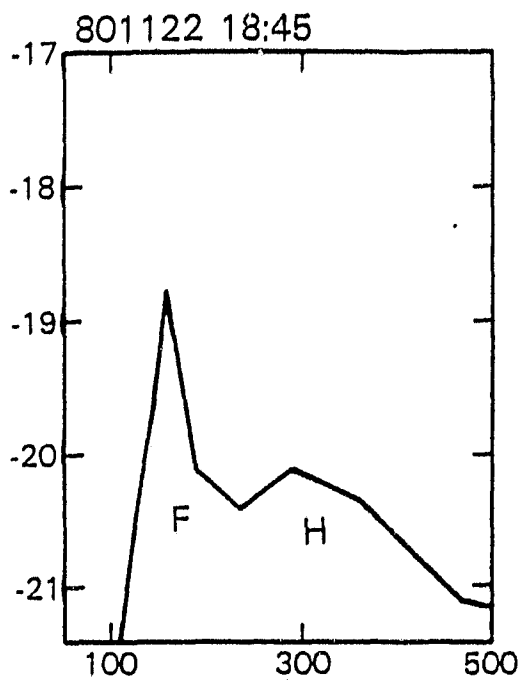
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LOG INTENSITY (WATTS/M<sup>2</sup>/Hz)



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LOG INTENSITY (WATTS/M<sup>2</sup>/Hz)

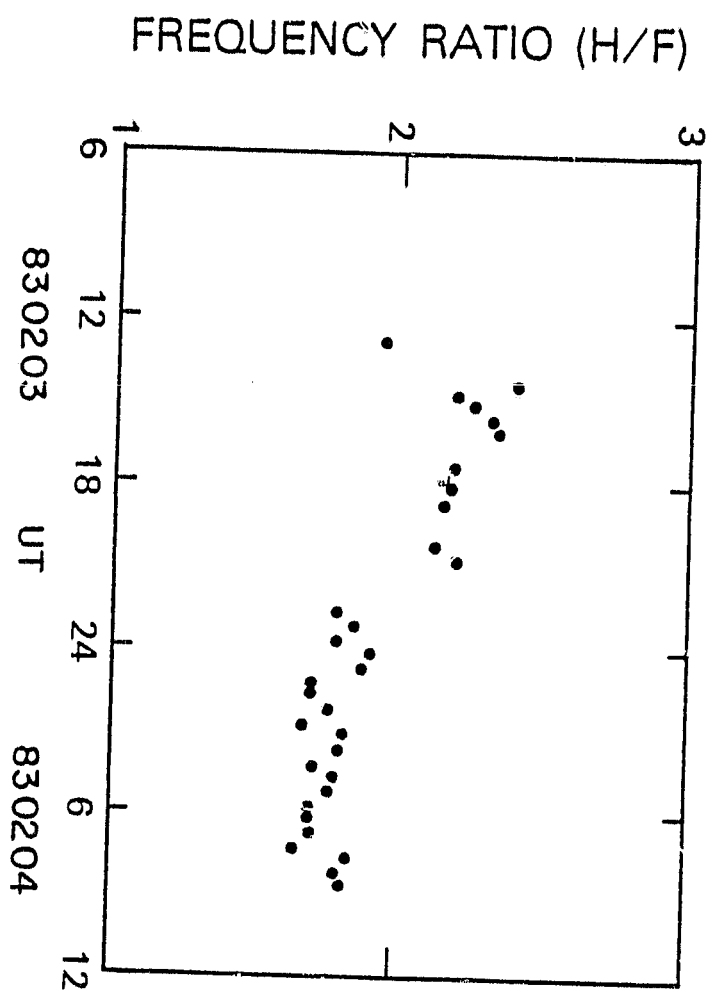


FREQUENCY (KHz)

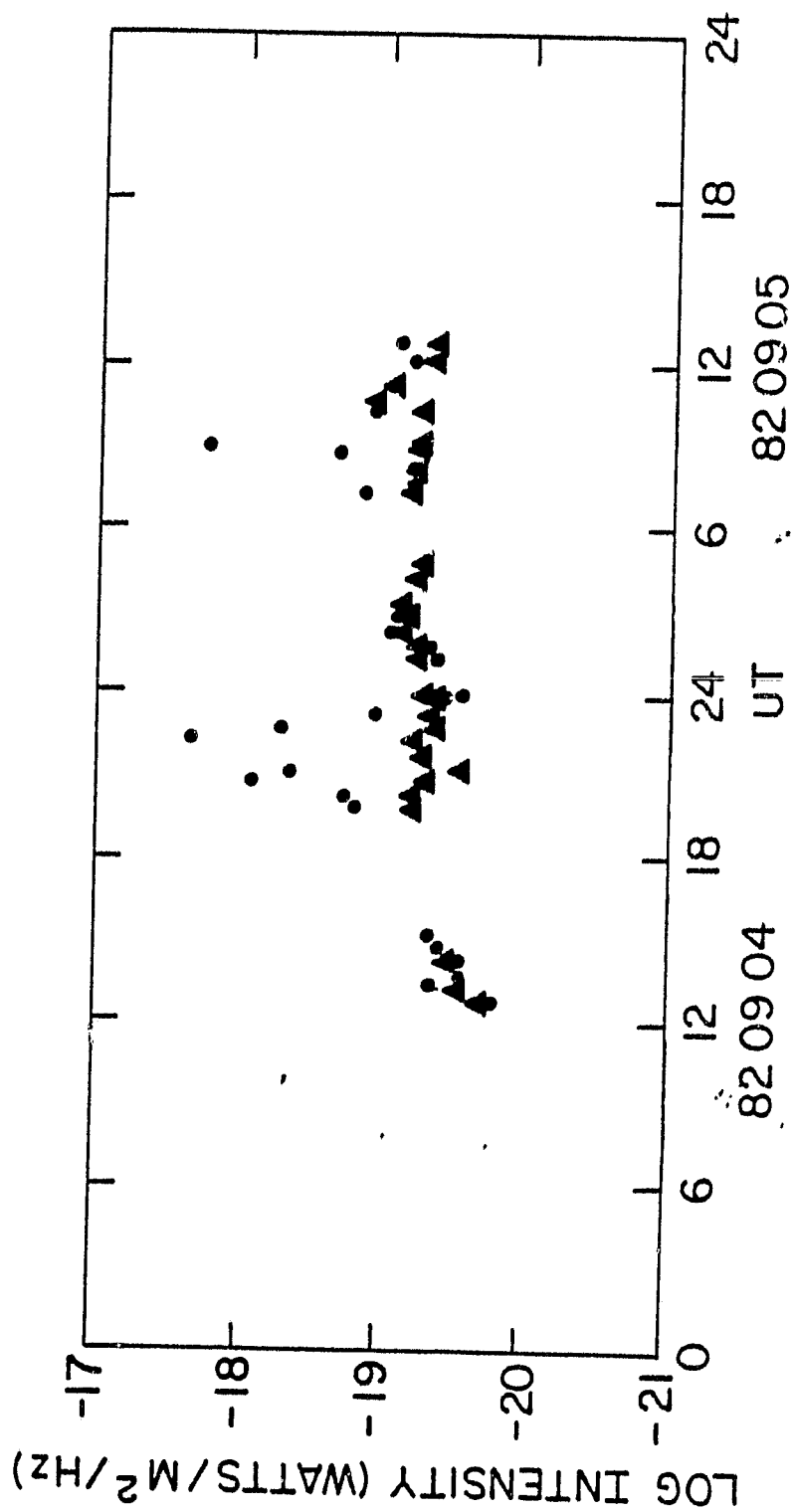
FREQUENCY (KHz)



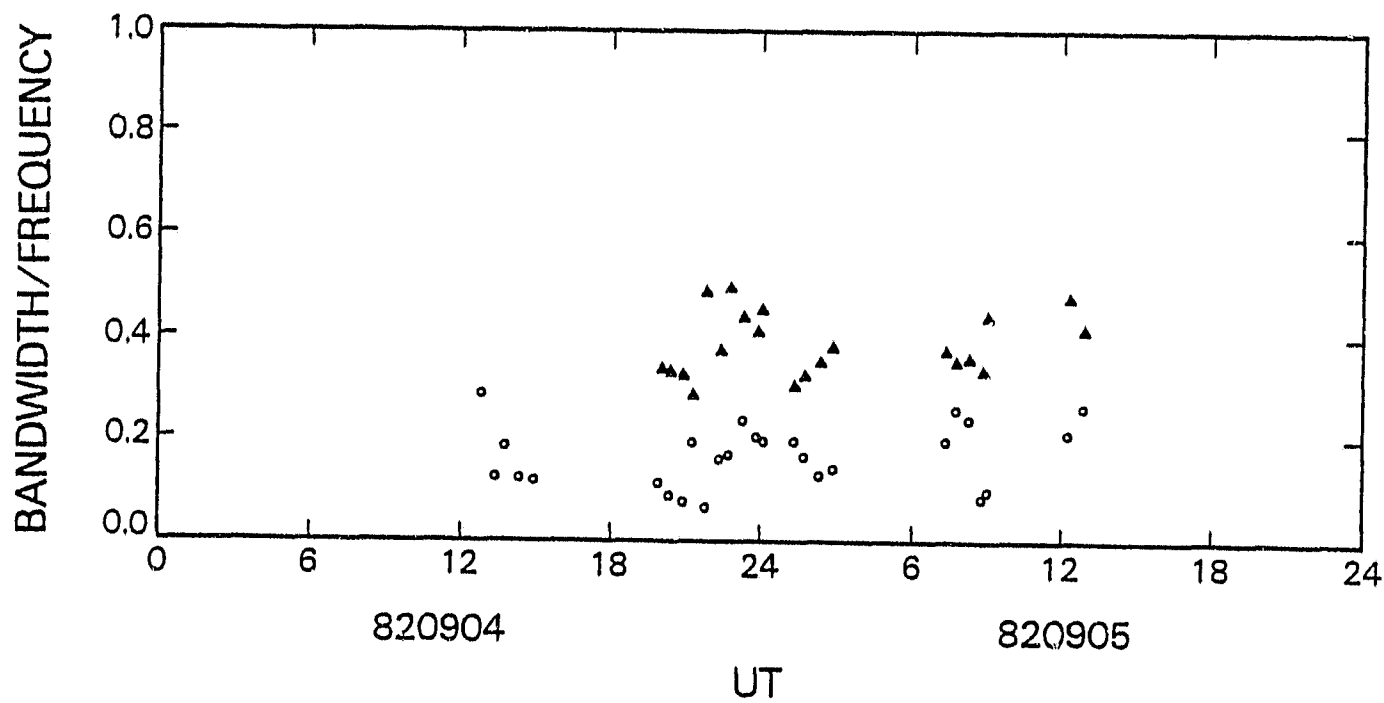
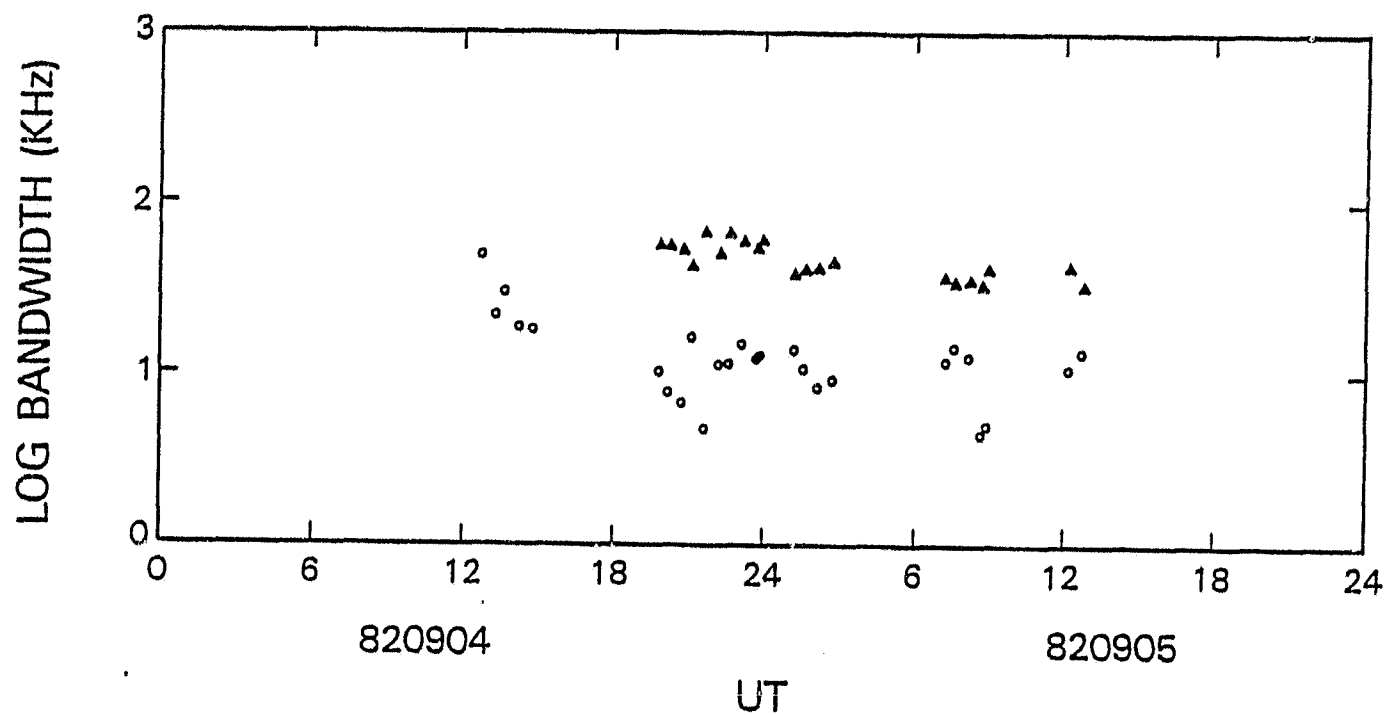
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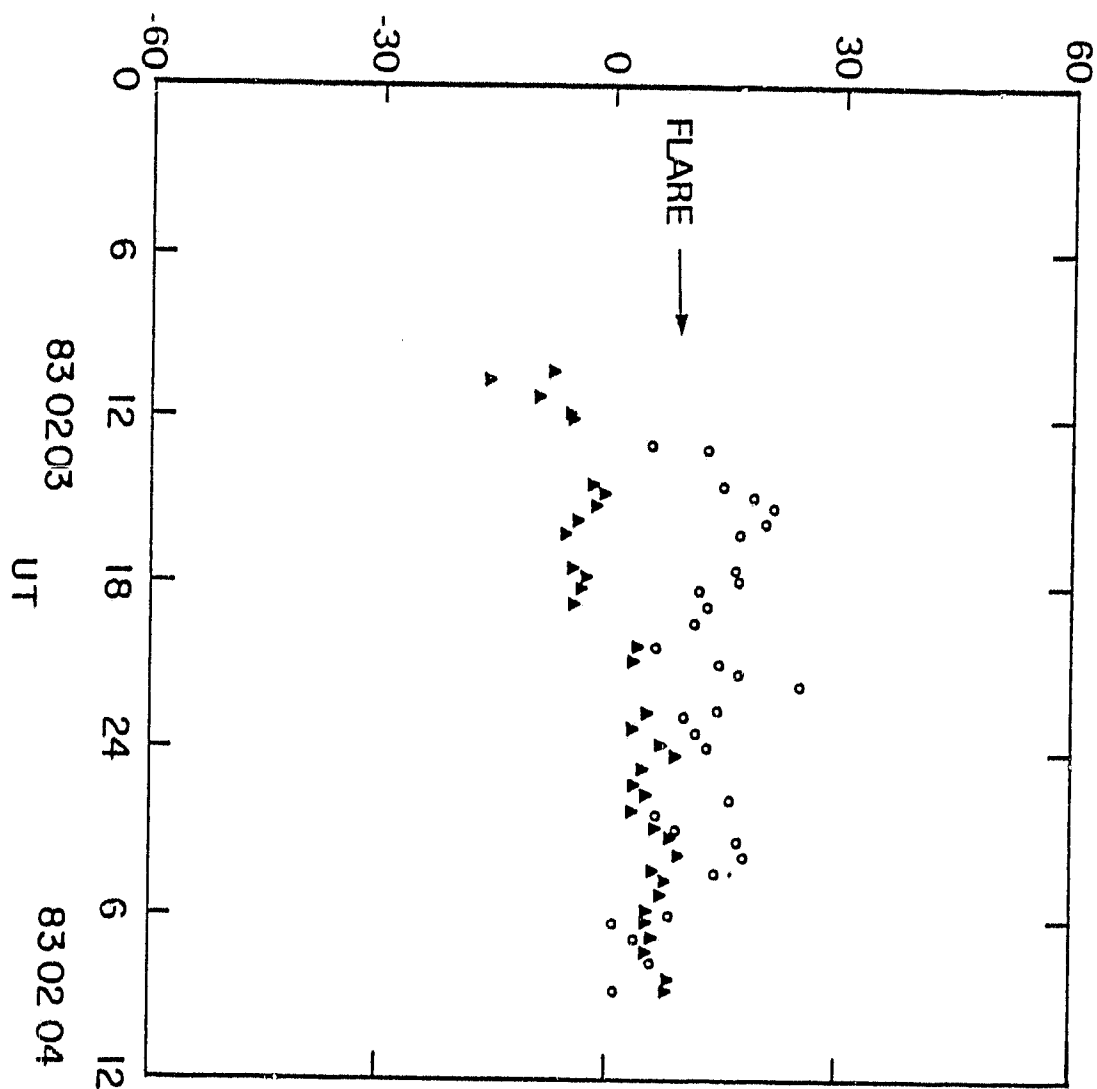


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LONGITUDE OF SOURCE CENTROID (DEGREES)



ORIGINAL PLATE (1)  
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ANGULAR SOURCE SIZE (DEGREES)

